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RESEARCH ARTICLE

Controlling reaching movements with predictable and unpredictable target motion in 10-year-old children and adults

Moritz M. Daum · Susanne Huber · Horst Krist

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Abstract We investigated interception behavior in adults and 10-year-old children. Participants had to intercept virtual targets moving on either a predictable (linear) or unpredictable (non-linear) path (with random direction changes). Targets moved at two different velocities, which varied randomly from trial to trial. Participants reached for the targets via a force-feedback device. Reaching movements for linearly moving targets in a block of linearly moving targets were compared with reaching movements for linearly moving targets in the context of non-linearly moving targets. Movement direction and maximum speed of the first sub-movement were analyzed as well as frequency of target hits and number of sub-movements. Unpredictable target motion caused faster movement speeds than predictable target motion for both children and adults. Additionally, unpredictable target motion caused children and adults to gear their initial movement direction further towards the current position of the target, while with predictable target motion, they geared their initial movement direction further ahead of the target towards an anticipated interception position. Together, these results suggest differential processing of predictable and unpredictable object behavior in an interception task, and that this differential processing is already in place in 10-year-olds.

Keywords Visuomotor control · Interception · Motor development

M. M. Daum · S. Huber · H. Krist
Department of Psychology,
University of Zürich,
Zürich, Switzerland

Present Address:
H. Krist
Department of Psychology,
University of Greifswald,
Greifswald, Germany

M. M. Daum (✉)
Department of Psychology,
Max Planck Institute for Human Cognitive and Brain Sciences, Stephanstr. 1a,
04103, Leipzig, Germany
e-mail: moritz.daum@cbs.mpg.de

Introduction

One major component of skilled action performance is the anticipation of future events. Movements have to be planned with regard to external forces and possible interferences (Lee 1993; von Hofsten 1993). This ability develops slowly from a more reaction-based movement control—where current incoming information is integrated into the ongoing action—to an anticipatory control (von Hofsten 1993). Nevertheless, infants already show rudiments of an anticipatory movement control: for example, at the age of 3 months, infants are able to track a moving object with smooth eye pursuit (Aslin 1981; Phillips et al. 1997; von Hofsten and Rosander 1997; Rosander and von Hofsten 2000, 2002).

An appropriate method for investigating anticipation behavior is to use interception tasks. Most of the research investigating human interception and timing behavior has used targets moving on linear paths with a constant velocity (e.g., Bairstow 1987, 1988; Smeets and Brenner 1995; Brenner et al. 2002). The present study was designed to investigate interception behavior with targets showing a non-predictable movement pattern similar to the escape movements of fleeing animals. In a figurative sense, catching a linearly rolling ball was compared to catching an escaping chicken. In this regard, the focus was on whether the knowledge of the respective target behavior leads to differences in action planning and hence in the initial part of the interception behavior. More specifically, are human interception movements adapted to the specific behavior of a moving object and are these interception movements geared differently according to target behavior? In addition, is this action planning and prospective control still developing at the age of 10 years or has it already reached an adult level at this age?

Reaching movements for stationary and moving objects are fundamental motor actions. Although they are simple movements, they involve almost all aspects of human motor control (Karniel and Inbar 1997). The path of the hand is close to a straight line and speed profiles are bell-shaped, single-peaked, and approximately symmetrical irrespective of movement direction, amplitude, or speed (Morasso 1981; Abend et al. 1982; Atkeson and Hollerbach 1985; Georgopoulos 1986). Reaching movements generally vary little within and between subjects (Miall and Haggard 1995), and variability tends to decrease with practice (Georgopoulos et al. 1981).

Whereas reaching for stationary objects is mainly determined by demands on spatial accuracy, successfully intercepting moving objects additionally requires coordination of time and space (Peper et al. 1994; Tresilian 1994; Carnahan and McFadyen 1996; Port et al. 1997). In various interception tasks, reaching for linearly moving objects has been studied by researchers interested in human motor control (see Schmidt 1988, for a review; Desmurget et al. 1998) and the development of perceptual-motor skills (Williams 1973; Dorfman 1977; Keogh and Sugden 1985; von Hofsten et al. 1998; von Hofsten 2001). This research has shown that reaching movements for linearly moving objects are anticipatory: during the first 50 ms, already, the reaching movement is geared towards a future position of the target and not to its momentary position (Bairstow 1987, 1988). The speed of reaching movements for moving objects is highly adapted to the object's velocity: objects that move with high velocity are approached faster than objects moving more slowly, even if participants are instructed to reach for the object as fast as possible (Smeets and Brenner 1995). The direction in which the hand moves appears to be primarily based on the target's position, whereas its acceleration is based on the target's velocity (Smeets and Brenner 1995; Brenner et al. 2002).

Developmental aspects of interception skills have been investigated in detail mostly by von Hofsten and colleagues (von Hofsten 1980, 1982, 1983; von Hofsten et al. 1998). Their research has shown that young infants are capable of manually intercepting a (slowly) moving object as soon as they begin to reach for stationary objects (von Hofsten and Lindhagen 1979). As in adults, infants' reaching movements have been shown to be anticipatory (von Hofsten 1980, 1983; Clifton et al. 1993). Although this rudimentary interception skill improves markedly between 4 and 8 months of age, most kinematic patterns of children's reaching movements do not assume an adult-like level before the age of 2 years. Children between the age of 2 and 12 years are able to intercept moving objects much like adults (Konczak et al. 1997; Konczak and Dichgans 1997), but they are still developing and honing their skills with respect to catching objects (Roberton and Halverson 1984; Haywood and Getchell 2001). Especially the ability to catch small objects at high velocities continues to develop at least until the age of 12 years (Bard et al. 1990; Strohmeyer et al. 1991). These improvements are based on advances in perceptual-motor abilities like prediction and extrapolation of trajectories (Williams 1973; Krist 1992) and on increasing cognitive control of the required motor skills.

Related to the interception task of the present study is a speed adjustment task used by Huber et al. (2003; see also Wilkening and Martin 2004). Children aged 10 years and adults had to set the speed of a moving car to a new speed so that it would reach a target line at the same time as a faster reference car. In their Experiment 1, Huber et al. (2003) showed that children's and adults' speed adjustments followed the normative pattern when responses had to be graded linearly as a function of the car's initial speed. In a non-linear condition, only adults' responses corresponded to the normative function. A simplification of the task in Experiment 2 enabled children to grade the speeds adequately. Huber et al. (2003) hypothesized that adults used an imagery strategy to redefine the task as an interception task in Experiment 1 and that it was the imagery demand that prevented most 10-year-olds from reaching the same level as adults. Although children at an age of 10 years and younger (Piaget and Inhelder 1966; Marmor 1975; Wilkening 1981; Black and Schwartz 1996), if not even infants (Baillargeon 1986; Hespos and Rochat 1997), are capable of mentally simulating object motions, in the view of Huber et al. (2003), 10-year-old children appear to still have difficulties to simultaneously simulate an object's motion *and* to adapt their action to the representation of the moving object.

In sum, basic perceptual-motor skills seem to reach an adult-like level from an early age on. More specific skills, however, like catching moving objects, planning an action, executing it as planned, simulating an object's motion, and adapting one's action to this simulation do not reach an adult level before the age of 10–12 years. Due to these facts, not only adults but also 10-year-old children were tested in the present experiment. In doing so we sought to shed new light on the developing competency of adapting one's interception behavior to different target behaviors.

In this experiment, it was of primary concern to assess how the predictability and speed of the target's motion influenced (a) the maximum speed and (b) the direction of the initial interception movement in 10-year-old children and adults. For the adult sample, the following predictions were made concerning speed and predictability effects.

Based on previous work by Smeets and Brenner (1995), who studied interception behavior with predictable target motion, we expected that both maximum speed and direction of the first sub-movement would depend on target speed. Faster objects should be intercepted with a higher initial maximum speed and at a greater angle, i.e., at an angle headed more towards an anticipated interception point and less towards the current target position. We further expected to find similar speed effects for both types of target motion.

As possible influences of the predictability of target motion on the programming of interception movements have not been studied yet, we derived our predictions concerning this variable from the basic assumption that adult performers are highly adept at adapting their motor planning to task demands (e.g., Meyer et al. 1988). A rational strategy to deal with unpredictable target motion is to narrow down one's anticipatory time window as predictability decreases. In the extreme case, when a target's behavior is completely unpredictable, i.e., when its subsequent spatial position is only constrained by continuity in space and time but not by inertia or any other regularity, there is no way to anticipate its future trajectory. Hence, the best one can do is to go straight for the target. We therefore predicted that adults would gear their initial sub-movements more towards the momentary target position with unpredictable than with predictable target motion (note that our "unpredictable" condition was actually partially predictable and not completely unpredictable, because the target always started moving on a linear path, see below).

Narrowing down one's anticipatory time window does not necessarily imply that one has to go faster, because one could plan for shorter sub-movements as well. However, especially when trying to catch an object that behaves like a chicken, i.e., tries to escape as one gets closer to it, the best strategy probably is to use a fast initial sub-movement to get as quickly as possible in the vicinity of the target object. If one is lucky, one intercepts the target immediately, and if not, one is in a good position to catch the object with additional sub-movements. Because the unpredictable target motion actually resembled the behavior of an escaping chicken in the present experiment and the target had to be intercepted before it disappeared from view, we predicted that adults would produce higher maximum speeds with their first sub-movements in the unpredictable than in the predictable condition.

Of course, we also expected a greater number of sub-movements and a smaller number of target hits in the unpredictable than in the predictable condition. Similarly, the number of sub-movements should increase and the number of target hits should decrease with the speed of the target.

No specific predictions were made for the sample of 10-year-old children. We considered it an empirical question how close their performance would come to that of our adult sample, and we were primarily interested to assess whether they would exhibit adult-like predictability and target speed effects on the initial speed and direction of their interception movements.

Methods

Participants

A total of 47 participants took part in this study: 23 adults (11 female and 12 male, mean age: 23 years 8 months, SD = 2 years 11 months) and 24 10-year-old children (12 female and 12 male fourth graders, mean age: 10 years 2 months, SD = 0 years 6 months). The adults were mostly undergraduate students from the University of Zürich and were paid for their participation. The children were recruited from classrooms (fourth grade) of an urban area of Switzerland (Zürich) and were rewarded with a small rubber ball. All children participated on a voluntary basis and with the consent of their parents. All participants reported normal or corrected-to-normal vision.

Apparatus

Stimulus scenes were generated on a Pentium II PC (256 MB RAM, Intergraph Intense 3D Pro GraphicBoard, Windows NT) using the OpenGL™ 3D-Graphics Library. Participants sat in front of a 21″ monitor (diameter: 56.1°, 1,152 × 864 pixels), viewing distance was ~50 cm. The animation was rendered at 30 Hz (scene update rate). Participants had to intercept a spherical object (target), which was presented at a visual angle of 1.5°. The target started from a so-called "home area", which was marked by a circle around the starting position with a cross section dimension of 10.9°. The starting position was located 22.6° from the lower border, 11.4° from the upper border, and 2.2° from the nearer right or left border of the monitor. The target moved with a constant velocity of either 19.3°/s (17 cm/s) or 27°/s (24 cm/s) and either to the left or to the right depending on the starting position (right or left, respectively). In order to intercept the target, the participants had to move an *interception object* of the same size as the target. This interception object was colored purple. Participants controlled the interception object via a PHANToM™ haptic interface (Type 1.5) using the index finger of their right hand (see Fig. 1). A thimble-like holder was attached to the device for this purpose. The force-feedback simulation was programmed with the Ghost™ library. The coupling between the translation of the holder connected to the force-feedback device and the movement of the interception object was linear (output rate of the PHANToM: 1,000 Hz). A translation of the holder would cause the interception object to translate on the display in the same manner [i.e., 1 cm in the PHANToM space corresponded to 1 cm (1.13°) on the display]. The degrees of freedom of movement of the holder were reduced to the frontoparallel plane of the computer screen so that only height, but not depth control was possible.

To limit the speed of participants' interception movements, motors built into the PHANToM haptic interface were set to produce a resistance of 2 N. The position of the interception object controlled via the holder was recorded at 200 Hz. The starting position of the interception object was placed at the lower border of the monitor on the respective side of the target's starting position (see Fig. 2). As soon as the target was intercepted, a computer generated beep was presented and the target movement stopped immediately. In the linear condition, the target was colored blue and moved on a straight and horizontal path. Target velocity and movement direction were held constant in each trial. In the non-linear condition, the target was colored orange and was programmed to show an escape behavior. It changed its direction as soon as the distance from the interception object fell below a minimal distance ($d_{\min}$) that was chosen randomly from the interval between 5.4° and 18.7° (see Fig. 2). The target changed its direction by an angle randomly chosen from the interval from 75° to 105° to the left or right of the previous direction.

Fig. 1 Experimental setup: the PHANToM™ haptic interface placed next to the computer screen

Procedure

All subjects were instructed in essentially the same way, except that the instructions given to the children were more redundant and tailored to their interests. All instructions were given orally by the experimenter. Each participant was tested individually. Order of condition and sex were counterbalanced across participants within each age group.

Participants were asked to intercept the moving target using the interception object. To make sure participants could estimate the target velocity, they were instructed not to start their interception movement before the target left its home area. This instruction was given in order to counter the strategy of relying on the target velocity from the previous trial (de Lussanet et al. 2001). Participant's interception movements were measured via the PHANToM haptic interface. In the linear condition, eight experimental trials were given; in the non-linear condition, a total of 40 experimental trials were given, in eight of which the target moved on a linear path—like in the linear condition. Only the data of these eight linear trials was included into the data analysis of the non-linear condition. The two conditions were presented separately in two experimental blocks. Target velocity and direction were varied randomly within each block of trials. To familiarize participants with the respective target behavior, eight practice trials were given at the beginning of each experimental block. In these practice trials, each of the four combinations of target velocity and starting position was presented twice in a randomized order.

Data analysis

The interception movement was analyzed with a sampling rate of 200 Hz. In the linear condition, all eight

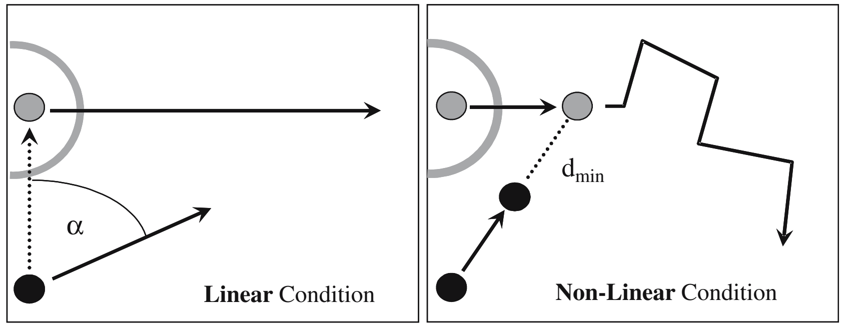

Fig. 2 Schematic illustration of the two predictability conditions: linear condition shown with α-value (*left*) and non-linear condition shown with minimum distance d_{min} (*right*)

experimental trials were analyzed. In the non-linear condition, only those eight trials were analyzed, in which the target moved linearly with no change of direction. From the raw data we calculated the onset time of the participant's movement, the movement direction of the first sub-movement, the maximum speed (peak velocity) of the first sub-movement, and the hit rates. According to the criteria used by Bairstow (1987, 1988) the onset of the participant's interception movement was defined as the instant at which the speed of the interception movement exceeded the minimal speed of 5.5°/s, which was about 6% of the average maximum speed of the interception movements.

To analyze the reaching speed, participants' maximum speed of their first sub-movement was used. The first sub-movement was defined as described by Meyer et al. (1988, p. 354).

The movement direction was calculated from the value of the angle α (α-value) between the vector of participants' movement direction at the velocity peak of the first sub-movement following the movement initiation (i.e., the vector between the participant's starting position and the position at the maximum speed of the first sub-movement), and the vector between participants' starting position and the target position at participants' movement onset (see Fig. 2). This is analogous to von Hofsten's (1980) β angle and to Bairstow's (1988) prediction angle. The measured α-value provides information about the initial direction of participants' interception movements. Smaller α-values indicate that the movement is headed more towards the actual target position, and larger α-values indicate a more "predictive" interception movement where the hand is geared towards an anticipated interception position.

Results

Maximum speed

The maximum reaching speed was analyzed using a 2 × 2 × 2 × 2 × 2 ANOVA (Age Group × Predictability of Target Motion × Target Velocity × Direction of Target Motion × Trial). The maximum speed of participants' first sub-movement varied with both target velocity and predictability of target motion (see Fig. 3). The maximum reaching speed was higher in the non-linear condition than in the linear condition, $F(1, 45) = 55.64$, $p < 0.001$, $\eta^2 = 0.55$, and higher for the faster targets than for the slower ones, $F(1, 45) = 82.42$, $p < 0.001$, $\eta^2 = 0.65$. Adults produced faster maximum reaching speeds than children, $F(1, 45) = 6.02$, $p < 0.05$, $\eta^2 = 0.12$ (adults: M = 86.97 cm/s, SD = 21.62 cm/s; children: M = 77.12 cm/s, SD = 18.65 cm/s). No further main effects or interactions were statistically significant (all *p*s > 0.08).

Movement direction

The direction of the first sub-movement was analyzed in the same way as participants' maximum speed of the first sub-movement. The results are shown in Fig. 4. The α-value was larger in the linear condition than in the non-linear condition, $F(1, 45) = 35.31$, $p = 0.001$, $\eta^2 = 0.44$. Participants aimed their interception movement clearly towards an anticipated interception point

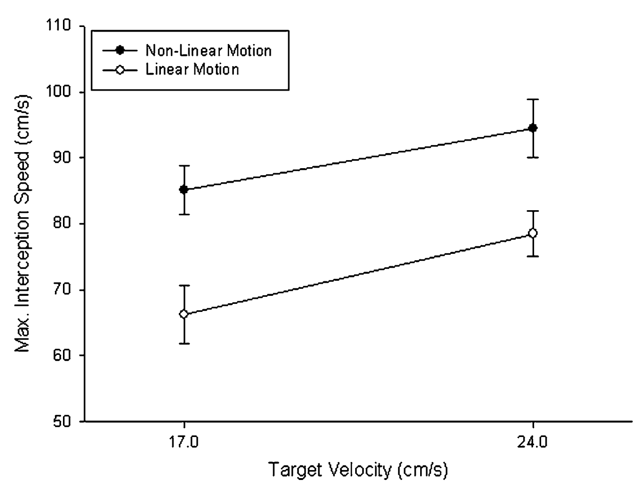

Fig. 3 Mean maximum speeds of the first sub-movement as a function of predictability and velocity of target motion (with standard error bars)

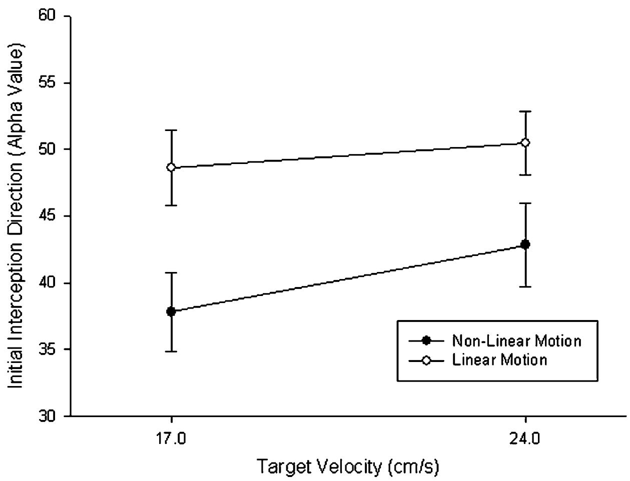

Fig. 4 Mean α-values as a function of predictability and velocity of target motion (with standard error bars)

in the linear condition, but approached the target more directly in the non-linear condition. The α-value was larger for faster targets than for slower ones, $F(1, 45) = 13.67$, $p = 0.01$, $\eta^2 = 0.23$. There was also a significant interaction of predictability of target motion and target speed, $F(1, 45) = 6.44$, $p < 0.05$, $\eta^2 = 0.13$. The effect of target speed was larger in the non-linear condition than in the linear condition. Unexpectedly, the target's motion direction had a significant influence on participants' α-values, $F(1, 45) = 56.11$, $p = 0.001$, $\eta^2 = 0.56$. The α-value was larger for targets moving to the left than for targets moving to the right. The interaction between the target's motion direction and the predictability of target motion was marginally significant, $F(1, 45) = 3.40$, $p = 0.07$, $\eta^2 = 0.07$. The effect of the target's motion direction tended to be smaller in the non-linear condition than in the linear condition.

The factor age was only marginally significant, $F(1, 45) = 3.29$, $p = 0.08$, $\eta^2 = 0.07$. Children tended to produce larger α-values than adults. There was no main effect of trial, $F(1, 45) = 2.83$, $p = 0.10$, $\eta^2 = 0.06$, but trial interacted significantly with age, $F(1, 45) = 5.38$, $p < 0.05$, $\eta^2 = 0.11$. Adults produced smaller α-values in the second trial of each condition (i.e., combination of target speed and motion direction), while children produced similar α-values throughout (adults, trial 1: $M = 43.48$, SD = 15.96, trial 2: $M = 41.22$, SD = 15.43; children, trial 1: $M = 47.47$, SD = 19.14, trial 2: $M = 47.83$, SD = 18.95). Trial also interacted significantly with the predictability of target motion, $F(1, 45) = 4.20$, $p < 0.05$, $\eta^2 = 0.09$. The predictability effect was greater in the second trial of each condition than in the first trial. Trial further interacted with the direction of target motion, $F(1, 45) = 4.52$, $p < 0.05$, $\eta^2 = 0.09$. The effect of the direction of target motion was larger in the first trial of each condition than in the second. No further interactions were significant (all *p*s > 0.19).

Hit rates and number of sub-movements

The number of sub-movements was counted per participant for both predictability conditions and it was assessed whether the target was hit within its visible motion path on the computer screen. In the non-linear condition, again, only those trials were analyzed in which the target moved on a linear path. The frequency of successful interceptions and the number of sub-movements per trial are shown in Fig. 5.

A 2 × 2 × 2 × 2 × 2 ANOVA (Age Group × Predictability of Target Motion × Target Velocity × Direction of Target Motion × Trial) with the latter four factors as within-subjects variables was performed on participants' frequency of target hits. As the data for each trial were dichotomous, interactions including all four within-subjects variables were not analyzed. No effect of predictability was found, $F < 1$. Participants were more likely to hit the target when it moved slowly than when it moved quickly, $F(1, 45) = 15.26$,

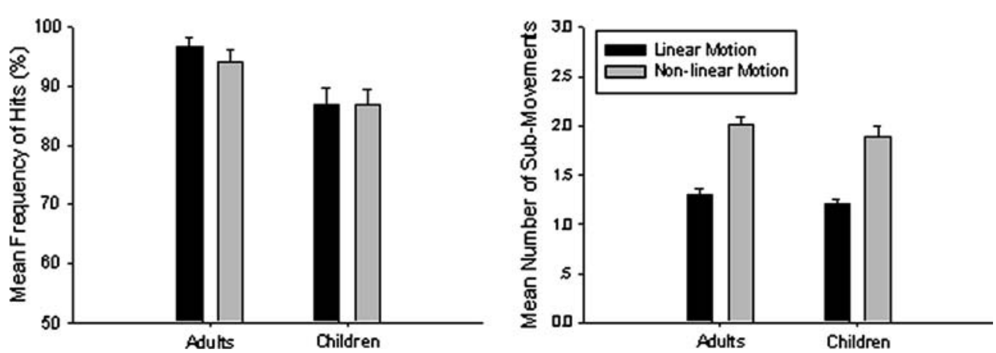

Fig. 5 Mean frequency of successful interception movements (*left panel*), and mean amount of sub-movements per age group and predictability condition (with standard error bars)

$p < 0.001$, $\eta^2 = 0.25$, and adults ($M = 0.95$, SD = 0.22) were more likely to hit the target than children ($M = 0.87$, SD = 0.34), $F(1, 45) = 8.03$, $p < 0.01$, $\eta^2 = 0.15$. Further, participants were more likely to hit the target in the second trial than in the first trial, $F(1, 45) = 50.89$, $p < 0.001$, $\eta^2 = 0.50$, and this difference was more pronounced in children than in adults, $F(1, 45) = 10.30$, $p < 0.01$, $\eta^2 = 0.19$. The interaction of target velocity and trial was significant, $F(1, 45) = 18.98$, $p < 0.001$, $\eta^2 = 0.30$, the increase of the probability to hit the target in the second trial was more pronounced with fast targets than with slow targets. And this difference was more distinct in children than in adults, $F(1, 45) = 6.21$, $p < 0.05$, $\eta^2 = 0.12$. No other significant main effects or interactions were found (all ps > 0.07).

Participants' number of sub-movements to intercept the moving target was counted for all trials irrespective of whether the target was actually hit or not. A $2 \times 2 \times 2 \times 2 \times 2$ ANOVA (Age Group × Predictability of Target Motion × Direction of Target Motion × Target Velocity × Trial) was performed on the number of sub-movements, with the latter four factors as within-subjects variables. There was a significant main effect of predictability of target motion, $F(1, 45) = 72.13$, $p < 0.001$, $\eta^2 = 0.62$. The number of sub-movements was larger in the non-linear condition than in the linear condition and also larger with the faster targets than with the slower targets, $F(1, 45) = 8.41$, $p < 0.01$, $\eta^2 = 0.16$. And there was a main effect of trial, $F(1, 45) = 19.03$, $p < 0.001$, $\eta^2 = 0.30$. The number of sub-movements was larger in the second than in the first trial, and this difference was larger in adults than in children, $F(1, 45) = 11.42$, $p < 0.01$, $\eta^2 = 0.20$ (adults, trial 1: $M = 1.47$, SD = 0.81, trial 2: $M = 1.92$, SD = 1.02; children, trial 1: $M = 1.74$, SD = 1.13, trial 2: $M = 1.80$, SD = 1.05). The interaction of predictability and direction was nearly significant, $F(1, 45) = 4.06$, $p = 0.05$, $\eta^2 = 0.08$; the predictability effect was more pronounced for targets moving to the left than to the right. The interaction of predictability and trial was significant, $F(1, 45) = 11.49$, $p < 0.01$, $\eta^2 = 0.20$; the increase in the number of sub-movements from the first to the second trial was larger with unpredictable than with predictable target motion. The interaction of target velocity and trial was also significant, $F(1, 45) = 5.86$, $p < 0.05$, $\eta^2 = 0.12$; the increase in the number of sub-movements from the first to the second trial was larger with slow targets than with fast targets. Except for a small and unsystematic four-way interaction of predictability, motion direction, target velocity, and trial, $F(1, 45) = 4.25$, $p < 0.05$, $\eta^2 = 0.09$, there were no further significant effects (all ps > 0.07).

Discussion

Children's and adults' interception behavior was investigated using targets moving either predictably or unpredictably in a desktop virtual environment. Participants used a PHANToM haptic interface to gear a spherical object towards the moving targets. It is important to note that, in the non-linear (unpredictable) condition, only those trials were analyzed and compared to the linear (predictable) condition, in which the target moved linearly, without a change of direction. Thus, there was no objective difference between the analyzed trials in the linear and the non-linear condition except for the context in which these trials were presented. The results of this study show that, overall, both children and adults differentiated between predictable and unpredictable target motion. The difference between the two target behaviors affected both participants' reaching speeds and reaching directions. The influence of the two predictability contexts was already discernible in the first sub-movement. This suggests that at least the first part of the reaching movement was preplanned according to prior knowledge about the behavior of the moving target. One can therefore conclude that the (initial) direction and speed of the interception movement is not only based on the target's position and velocity (Smeets and Brenner 1995; Brenner et al. 2002) but also on the interceptor's knowledge about the respective target behavior. The predictability of the moving target's behavior was not varied within a block of trials; therefore it could be used as a constant variable in the planning of the interception movement. The immediate visual information was only needed to assess the target velocity.

The results suggest that in the linear condition, where the target moved predictably, children and adults anticipated the movement of the target and geared their interception movement towards an interception position located ahead of the object's momentary position, adjusting the speed of their interception movement adequately. In contrast, and as predicted, children and adults reached much faster in the non-linear condition than in the linear condition and aimed the direction of their interception movement more towards the momentary target position. In the non-linear condition, participants apparently seemed to use a more risky and less accurate strategy as they tried to get as quickly as possible close to the moving target in order to reduce the remaining distance to the target after its first change of direction. The larger number of sub-movements in this condition supports this conclusion. Through an interaction with the target, children and adults established predictive knowledge about the respective target behavior and used this knowledge to adjust the direction and the speed of their interception movements.

Participants adapted their reaching movements not only to the predictability but also to the velocity of the target motion. The maximum speed of their first sub-movement was higher and the direction of their first sub-movement was geared further ahead with faster targets than with slower ones. In addition, with slower target velocity, participants were more likely to intercept the target and the number of sub-movements was smaller.

Overall, children and adults showed very similar results. Both age groups adjusted the speed and direction of their interception movement in the same way depending on the predictability and velocity of the target's motion. Age differences were primarily found with respect to the reaching speed and the hit rate. Children produced a slower reaching speed than adults and they were less likely to hit the target. The age difference in the reaching speed might be explained by the fact that at the age of ten, children are smaller and weaker than adults. Perhaps, they had more difficulty coping with the resistance of the PHANToM haptic interface. It is also conceivable that children adapted the speed of their movements not only to the target behavior but also to their own motor capabilities. By programming relatively slow movement speeds they might have compensated for a relatively high variability in their motor outputs (e.g., Woodworth 1899), thereby trading speed for accuracy (cf., Meyer et al. 1988). The fact that children's hit rates were still well below those of adults does not contradict this interpretation because of the timing constraint imposed by the interception task and the possibility that the lower precision could not completely be compensated for. Overall, our results indicate that at the age of 10 years, perceptual-motor skills used in the planning of an interception action do not crucially differ from adults' competencies. Compared to adults, children's performance is mainly limited in terms of their smaller body proportions and perhaps their greater output variability. Our results differ from those obtained by Huber et al. (2003) who found that it was the imagery demand of their task that prevented 10-year-old children to reach the same level as adults. Therefore, the different results can be explained by the fact that there was no comparable imagery demand in the present interception task.

The direction of target motion (left versus right) influenced the direction of the initial interception movement. One possible explanation for the difference between these two movement directions is that the arm movement is subject to different biological constraints of the upper limb and the combination of shoulder and elbow joints (Hogan 1985). Thus different reaching directions in response to the direction of target motion might be explained by this postural constraint.

There is some evidence that participants' movement planning changed over trials. The maximum speed of the first sub-movement did not differ from the first to the second trial, and there was no main effect of trial regarding the reaching direction either. However, the predictability effect on the reaching direction increased and the effect of the target's motion direction decreased from the first to the second trial. The most distinct trial effects were found with respect to participants' hit rates. The frequency of hits increased from the first to the second trial and the number of sub-movements was larger in the second trial than in the first trial.

Participants seemed to have learned about the target's behavior already in the practice trials, as they differentiated between the two target behaviors already in the first trial of each condition. However, this process was not finished after the practice trial phase as mainly the increase of the hit rates over trials showed. Interestingly, this learning process from the first to the second trial was age-dependent. Adults' reaching direction changed over trials while children's did not. A similar age-dependent effect pertained to the number of sub-movements: children did not increase the number of sub-movements from the first to the second trial as much as adults did. In conjunction with the result that adults also increased their hit rates more than children, these age by trial interactions suggest that adults are better able to adapt to the experimental task demands than children. Taken together, our age-related findings indicate that, in their interception behavior, 10-year-old children consider a target's behavior in a similar way as adults but that they have not yet reached an adult-level with respect to speed, accuracy, and the capacity to fine-tune their behavior over trials.

In sum, human interception behavior appears to be adaptive with respect to the predictability of a target's motion. Both, the initial direction and speed of an interception movement are adjusted accordingly. Ten-year-old children's interception behavior does not appear to be fundamentally different from adults' in this respect. To shed more light onto developmental aspects, however, more research is needed that should include younger age groups and introduce systematic task variations.

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